

The Nuclear Cryogenic Propulsion Stage

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The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. A first generation Nuclear Cryogenic Propulsion Stage (NCPS) based on NTP could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Characteristics of fission and NTP indicate that useful first generation systems will provide a foundation for future systems with extremely high performance. The role of the NCPS in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NCPS project could help enable both advanced NTP and advanced Nuclear Electric Propulsion (NEP). Nuclear propulsion can be affordable and viable compared to other propulsion systems and must overcome a biased public fear due to hyper-environmentalism and a false perception of radiation and explosion risk.

Nomenclature

<i>CFEET</i>	= Compact Fuel Element Environmental Test
<i>DOE</i>	= Department of Energy
<i>HAT</i>	= NASA Human Architecture Team
<i>HIP</i>	= Hot Isostatic Press
<i>NASA</i>	= National Aeronautics and Space Administration
<i>NCPS</i>	= Nuclear Cryogenic Propulsion Stage
<i>NTP</i>	= Nuclear Thermal Propulsion
<i>NTR</i>	= Nuclear Thermal Rocket
<i>NTREES</i>	= Nuclear Thermal Rocket Element Environmental Simulator
<i>PEC</i>	= Pulsed Electric Current
<i>SLS</i>	= Space Launch System

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I. Introduction

Development efforts in the United States have demonstrated the viability and performance potential of NTP systems. For example, Project Rover (1955–1973) completed 22 high power rocket reactor tests. Peak performances included operating at an average hydrogen exhaust temperature of 2550 K and a peak fuel power density of 5200 MW/m³ (Pewee test), operating at a thrust of 930 kN (Phoebus-2A test), and operating for an accumulated time of 109 minutes (NF-1 test).¹¹ Results from Project Rover indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse greater than 900 s would be feasible. Excellent results have also been obtained by Russia. Ternary carbide fuels developed in Russia may have the potential for providing even higher specific impulses.

Many factors would affect the development of a 21st century nuclear thermal rocket (NTR). Test facilities built in the US during Project Rover are no longer available. However, advances in analytical techniques, the ability to utilize or adapt existing facilities and infrastructure, and the ability to develop a limited number of new test facilities may enable a viable development, qualification, and acceptance testing strategy for NTP. Although fuels developed under Project Rover had good performance, advances in materials and manufacturing techniques may enable even higher performance fuels. Potential examples include cermet fuels and advanced carbide fuels. Precision manufacturing will also enable NTP performance enhancements.

NTP will only be utilized if it is affordable. Testing programs must be optimized to obtain all required data while minimizing cost through a combination of non-nuclear and nuclear testing. Strategies must be developed for affordably completing required nuclear testing. A schematic of an NCPS engine is shown in Figure 1.

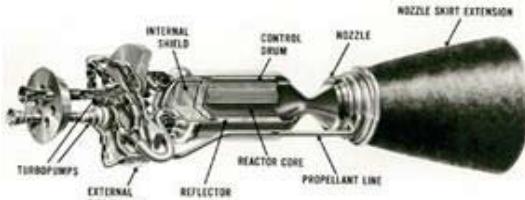


Figure 1. Schematic of an NCPS Engine.

II. The Nuclear Cryogenic Propulsion Stage Project

NASA's Nuclear Cryogenic Propulsion Stage (NCPS) project was initiated in October, 2011, with the goal of assessing the affordability and viability of an NCPS. Key elements of the project include 1) Pre-conceptual design of the NCPS and architecture integration; 2) Development of a High Power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator (NTREES); 3) NCPS Fuel Design and Testing; 4) NCPS Fuels Testing in NTREES and the Compact Fuel Element Environmental Test (CFEET) system; and 5) Affordable NCPS Development and Qualification Strategy. The NCPS project involves a large (~50 person) NASA/DOE team supplemented with a small amount of procurement funding for hardware and experiments. In addition to evaluating fundamental technologies, the team will be assessing many aspects of the integrated NCPS, and its applicability to enable NASA architectures of interest.

A. Pre-Conceptual Design of the NCPS and Architecture Integration

The NCPS is an in-space propulsion system/stage using fission as the energy source to heat propellant (hydrogen) and expand it though a nozzle to create thrust. The increase in engine performance available from even a first generation NCPS would enable ambitious exploration missions, both robotic and human. It is the intent of the NCPS project to develop a pre-conceptual design of a first generation stage with one or more nuclear thermal rocket(s) capable of interfacing with soon to be available launch vehicles and possible payloads and missions. The design must utilize technologies that are readily available with minimal risk to development. The design must take into account the development viability/feasibility, affordability, and potential reusability. A strategic method of development must be considered; assessing both commonality and scalability for miniaturization or growth. Other strategic considerations are the testing approach (a combination of terrestrial and space testing to validate the engine) and the need for sustained funding.

¹¹ Koenig D. R. (1986) Experience Gained from the Space Nuclear Rocket Program (Rover), LA-10062-H, Los Alamos National Laboratory, Los Alamos, NM

The NCPS must show relevance to the U.S. space exploration goals and must provide a development path toward a feasible, affordable, and sustainable Nuclear Cryogenic Propulsion Stage. United States' National Space Policy (June 28, 2010, pg. 11) specifies that NASA shall: By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth. The NCPS design will focus on ensuring maximum benefit to human Mars mission, although the NCPS could have numerous other applications as well.

NCPS mission analysis and definition will stay synchronized with the NASA Human Architecture Team (HAT) for application toward future human missions and the currently developing Space Launch System (SLS). The NCPS will provide input to SLS future block upgrades to enhance efficiency for volume and mass constraints that will reduce the number of launches for a mission utilizing the NCPS.

NCPS system trade and analysis will naturally optimize the efficiency of the system to accomplish the mission. The sensitivity of stage performance to specific impulse, engine thrust-to-weight ratio, and other parameters will be assessed to accomplish the mission and eventually define the actual size and weight of the system. The design of the NCPS will favor proven and tested technologies and the design will also identify critical technologies that will be required for development.

A historical perspective for a common, scalable fuel element will help provide flexibility in design. During the Rover program, a common fuel element / tie tube design was developed and used in the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968).

NASA and DOE are investigating a similar approach: design, build, ground and then flight test a 25 klbf-class engine that if clustered can be used for human missions. The NCPS must be optimally sized to ensure that it provides significant benefits to a wide variety of potential exploration missions, but can be adjusted in size with minimal changes to avoid unnecessary cost in re-development if possible.

The stage will need to leverage technologies from other programs and projects. Some specific technologies that are important for the NCPS are listed below:

- Cryogenic Storage (long duration storage, cryo-coolers, zero boil-off, zero leakage)
- Automated rendezvous & docking
- Radiation hardening of electronics
- Radiation shielding
- Enhanced System Health and Status Sensor/ Post operation/test remote inspection evaluation

The NCPS must take maximum advantage of technologies, components, and subsystems that are developed elsewhere in the architecture, as well as provide input and requirements to those technologies to obtain the capabilities needed for effective integration of NTP. The NCPS must also stay connected to the SLS and upper Cryogenic Propulsion Stage (CPS) projects to take advantage of common elements and to leverage technologies and configurations to reduce cost.

To support the NCPS design effort, available analytical tools will be enhanced and refined. The Department Of Energy (DOE) has developed sophisticated computer modeling tools for nuclear system design. Since the initial fuel elements under consideration are very similar to the past work accomplished under the Rover/NERVA and other programs, the NCPS will be able to take advantage of these available models. NASA has many rocket system simulation tools. These computational modeling tools from DOE and NASA will be used in conjunction to respond quickly to needed trade studies and mission analysis.

One engine system model under consideration is the closed expander cycle, which derives fluid-pumping power from excess heat generated within the engine and passes the entire propellant flow through the nozzle. The cycle is currently of interest due to its high Isp performance. However, several other candidate cycles have been considered in the past and will be evaluated. Also, hydrogen is the most desirable propellant based on its thermodynamic properties; similarly for high Isp performance. However, hydrogen is also very challenging to store for long duration missions without significant boil-off losses and will require technology refinement. Liquid hydrogen also has a very low density and high volume tanks are advantageous for many missions. Other potential propellants will be evaluated in the engine balance studies, and in-situ propellant usage is also a consideration.

The safety of all rocket engines (including nuclear engines) is paramount. Although a nuclear engine is essentially non-radioactive prior to operation at significant power, the engine must be designed to avoid inadvertent start. This is particularly true for times when individuals could be in close proximity to the reactor, such as launch processing. Safety of the nuclear engine will be ensured via design and by drawing on over seven decades of reactor operating experience.

Crew health and safety may benefit from the use of an NCPS. The NCPS may enable shorter mission times (reducing crew exposure to microgravity, cosmic rays, solar flares, and other hazards) or increased payload mass (allowing for increased shielding, supplies, or equipment).

B. Development of a High Power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator

A high temperature, high power density fissile fuel form is a key technology for an NCPS. Fuel life and performance is largely limited by mass loss in a hot gas/cyclic environment. Hence a major milestone of the NCPS project is the completion of the 1-MW Nuclear Thermal Rocket Element Environmental Simulator (NTREES) test chamber. The purpose of the NTREES facility (which also includes an arc heater and the Compact Fuel Element Environmental Tester, CFEET) is to perform realistic non-nuclear testing of nuclear thermal rocket (NTR) fuel elements and fuel materials. Although the NTREES facility cannot mimic the neutron and gamma environment of an operating NTR, it can simulate the thermal hydraulic environment within an NTR fuel element to provide critical information on material performance and compatibility.

NTREES recently complete an Operational Readiness Inspection (ORI), and the upgrade is nearing completion. Once fully operational, the 1-MW NTREES test chamber will be capable of testing fuel elements and fuel materials in flowing hydrogen at pressures up to 1000 psi, at temperatures up to and beyond 3000 K, and at near-prototypic reactor channel power densities. NTREES will be capable of testing potential fuel elements with a variety of propellants, including hydrogen with additives to inhibit corrosion of certain potential NTR fuel forms; however the focus of FY 2014 activities will be on pure hydrogen propellants.

The NTREES facility is licensed by the Nuclear Regulatory Commission (NRC) to test fuels containing depleted uranium. It includes a pyrometer suite to measure fuel temperature profiles and a mass spectrometer to help assess fuel performance and evaluate potential material loss from the fuel element during testing. Additional diagnostic upgrades planned for NTREES include the addition of a gamma ray spectrometer located near the vent filter to detect uranium fuel particles exiting the fuel element in the propellant exhaust stream and to provide additional information of any material loss occurring during testing. Using propellant fed from gas storage trailers located external to the facility, NTREES is configured to allow continuous, uninterrupted testing of fuel elements for any desired length of time. A picture of the current NTREES primary chamber configuration is shown in Figure 2.



Figure 2. Nuclear Thermal Rocket Element Environmental Simulator.

An additional test facility associated with NTREES is an operational arc heater (Figure 3) that is capable of flowing hot hydrogen over a material or fuel sample at a hydrogen gas temperature of up to 3160 K for approximately 30 minutes. This facility could be used for the preliminary vetting of material samples. Also available is CFEET, capable of testing small fuel samples at high temperatures in a hydrogen environment (Figure 4).

This project will also develop a detailed understanding of the energy deposition and heat transfer processes in NTREES, along with effects on material mechanics and fluid/material interaction, to better improve future test conditions and obtain as much information as possible to accurately extrapolate non-nuclear test data to real reactor conditions.

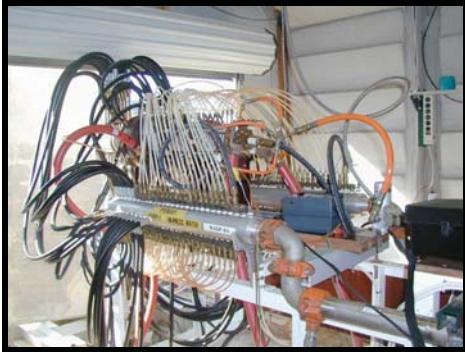


Figure 3. Arc Heater.

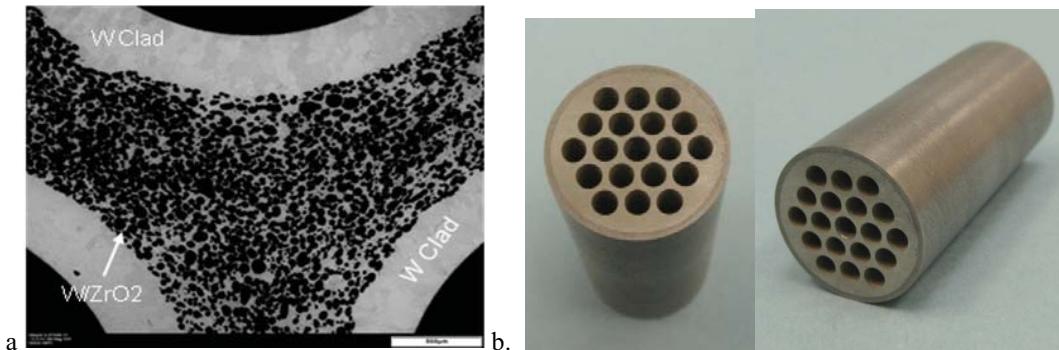


Figure 4. Compact Fuel Element Environmental Test facility (CFEET)

C. NCPS Fuel Design / Fabrication

Early fuel materials development is necessary to validate requirements and minimize technical, cost, and schedule risks for future exploration programs. The development of a stable fuel material is a critical path, long lead activity that will require a considerable fraction of program resources. The objective of the NCPS Fuel Design and Fabrication task is to demonstrate materials and process technologies for manufacturing robust, full-scale CERMET and graphite fuel elements. The elements will be based on the starting materials, compositions, microstructures, and fuel forms that were demonstrated on previous programs. The development will be a phased approach to recapture key technologies and produce quality fuels. Samples will then be tested in flowing hot hydrogen to understand processing and performance relationships. As part of this demonstration task, a final full scale element test will be performed to validate robust designs. These demonstrations are necessary to enable a future fuel material down select and a potential follow on non-nuclear ground test project. A major focus of the NCPS project is the use of a highly integrated NASA/DOE fuels development team. The goal is to enhance and utilize existing infrastructure and capabilities to minimize cost.

Current research at MSFC and INL is focused on developing fabrication processes for prototypical W/UO₂ CERMET fuel elements. CERMETS are typically formed by densification of powders using Powder Metallurgy (PM) processes. Tungsten based CERMETS with surrogate ceramic particles have been fabricated to near theoretical density using Hot Isostatic Press (HIP) and Pulsed Electric Current (PEC) techniques. During HIP, the CERMET powders are consolidated in sacrificial containers at 2000°C and pressures up to 30 ksi. The PEC process consists of high speed consolidation of powders using DC current and graphite dies. For both HIP and PEC processing, the powder size and shape, powder loading, and processing parameters significantly affect the quality and repeatability of the final part. Figure 5 shows a typical microstructure and image of a net shape consolidated CERMET part. The part is a 19 hole configuration that had uniform shrinkage during consolidation and good tolerance on the flow channel geometry.



**Figure 5. a) Micrograph of a W/60 vol% ZrO₂ CERMET with integral W claddings
b) Consolidated W/40 vol% HfN CERMET sample.**

The nature of this initial task is rapid materials and process screening as a precursor to the detailed development that will be required to fully optimize and qualify a CERMET fuel. CERMET materials and processes were

demonstrated at subscale level on previous efforts, but there are significant technical and programmatic challenges for key technologies. Some of the materials and process approaches being developed to maximize performance are the size of the fuel particles and resultant shape in the consolidated part, CVD tungsten coating of spherical UO₂ particles prior to consolidation, complete surface cladding of the elements with tungsten, and additions of small amounts of fuel particle and matrix stabilization materials such as Gd₂O₃.

Significant work is also being done at ORNL to recapture Rover/NERVA graphite composite fuel materials. Various graphite based fuels consisting of UO₂, UC₂, or (U, Zr)C particles in a graphite matrix were tested in the Rover/NERVA program. The materials were successfully demonstrated in full scale nuclear test engines. However, the fuel materials and fabrication technologies are not currently available. The NCPS task is focused on developing the graphite composite extrusion and ZrC coating capabilities. The composite fuel matrix is a carbide-based ceramic fuel composition consisting of uranium carbide, zirconium carbide and graphite materials. Subscale matrix samples are being fabricated and tested to demonstrate microstructure and properties. In parallel, coating trials are being performed on short elements for hot hydrogen testing at MSFC. The goal is to validate recapture of the graphite composite fuel materials using full scale testing of a Rover/NERVA fuel element. Figure 6 shows images of Phoebus reactor fuels from the 1960s.

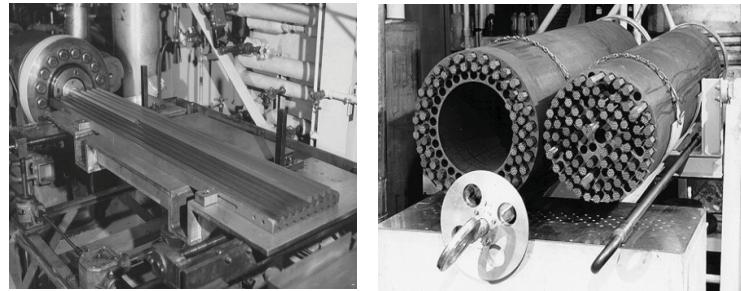


Figure 6: Images of the Rover/NERVA Phoebus Reactor fuels.

D. NCPS Fuels Testing in NTREES

Testing in NTREES will range from fuel sample testing using CFEET to the testing of near-prototypic fuel elements. A primary goal of the testing is to demonstrate adequate fuel performance and to increase confidence in fuel system designs (e.g. materials, coatings, geometries) prior to potential nuclear testing. CERMET and graphite composite samples will be thermal cycle tested in a static and flowing environment. Several iterations of testing will be performed to evaluate fuel mass loss impacts from density, microstructure, fuel particle size and shape, chemistry, claddings, particle coatings, and stabilizers. Initial subscale testing is being performed in the CFEET system. The CFEET test samples will be typically 0.75" across the flats and up to 3" long for solid slug and prototypic 7-hole channel configurations. The 7-hole channel configuration was chosen for CFEET screening to rapidly evaluate thermal cyclic affects on prototypic geometries from surface vaporization, diffusion/migration, and cracking. Testing has shown that fuel mass loss is significantly impacted by thermal cycling and geometry. The prototypical geometry will be much more susceptible to cracking induced migration and volatilization of the exposed fuel particles. The fuel materials and forms such as coated particles, claddings, and stabilizers being evaluated on this effort have all been demonstrated to control fuel migration and loss. The initial screening is not to determine or characterize specific modes of fuel loss or mechanisms. The intent is to verify performance improvements of the materials and processes prior to expensive full scale fabrication and testing. Posttest analysis includes weight percent fuel loss, microscopy (SEM, EBSD, and EDS), and dimensional tolerance and cracking.

Subsequent testing of full scale fuel elements will be performed in NTREES. The test samples will be based on the Rover/NERVA and ANL 200MW designs. The goal is to benchmark performance in NTREES for comparison to future materials and process improvements, alternate fabrication processes, and other fuel materials of interest. The iterative materials and process development, CFEET screening, and NTREES testing is anticipated to continue into FY 2015 and beyond. A photograph of a W / UO₂ CERMET sample undergoing testing in CFEET is shown in Figure 7.

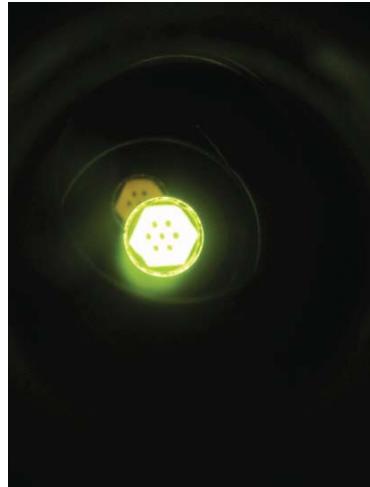


Figure 7: W / UO₂ sample testing in CFEET.

E. Affordable NCPS Development and Qualification Strategy

As previously noted, both the US and Russia have conducted highly successful NTR ground test and technology development programs. Although all of those programs were cancelled prior to flight, the cancellation typically occurred because the mission requiring NTP was cancelled, not because of insurmountable issues associated with the NTR. However, if NTP is to be used, its development, qualification, and utilization must be affordable and done in a way that is technically, programmatically, and politically acceptable.

The combination of emerging technology and the relatively modest thrust needed to support a human Mars mission (if a cluster of engines is used) allows for two potential options that could be enabling for eventual utilization of NTP. First, it appears feasible to use low-enriched uranium (LEU) in certain NTR systems instead of highly enriched uranium (HEU). In addition to greatly increasing the political acceptance of NTP, the use of LEU will significantly increase programmatic flexibility and significantly decrease programmatic uncertainties associated with the use of HEU. These factors are expected to reduce the cost of NTR development, qualification, and utilization.

The second option (primarily enabled by the modest thrust levels) is to fully contain the hydrogen that is exhausted during an engine ground test. Although the integrated containment system is highly sophisticated, the basic approach is to burn the hydrogen after it leaves the engine and condense the resulting steam. Any fission products released from the fuel during testing would be contained in the water and the overall containment system. Standard techniques would then be used to perform any required decontamination. An initial schematic of the fully contained exhaust system is shown in Figure 8.

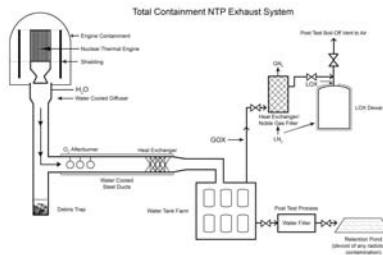


Figure 8. Option for Fully Containing NTR Exhaust During Ground Testing.

Lessons learned have been acquired from the J-2X rocket engine program, ARES 1-X Test Flight Program, and X-43A Flight Demo Program. The major factors form the lessons learned include the following: Follow NASA standards unless deviation has concurrence from the chief engineer and safety officer, start with low safety factors and evolve, upfront involvement from Safety Mission Assurance (including Risk Management) and Systems Engineering Integration, test development engines to the extremes and test two certification engines for flight with double the burn duration and double the number of starts.

The NTP test topology is shown in Figure 9. Past NTP development programs had in-depth testing planned involving a ground test complex with a special reactor to test fuel elements, a nuclear furnace for material characterization and critical assemblies to test reactor physics. To save time and money, the current plans are to

avoid having a nuclear furnace and fuel element reactor. Focus on non-nuclear testing of the fuel elements, followed by irradiation specimen testing using existing facilities, and use an existing reactor for sub-element testing. Final fuel element testing will take place at the full scale ground test facility.

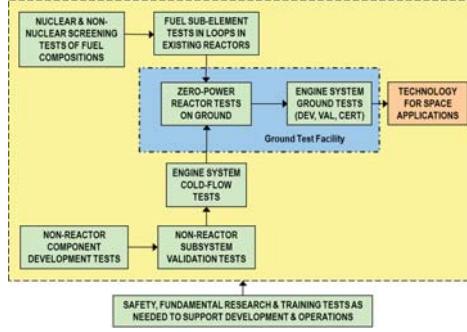


Figure 9. NTP Test Topology.

In addition to ground testing a full scale NTP engine, a flight demonstration is being investigated to help qualify the engine system and possibly used by a potential customer for a robotic mission. The flight demonstration would use the same NTR engine being developed to support a human Mars mission, but would have the option of running de-rated either in terms of thrust or Isp. The flight demo would also allow operation of a high area ratio nozzle, which is not possible in ground testing. Advanced instrumentation and robotics is being investigated to use on the NTP flight demo for inspection of the major engine components. Figure 10 shows similar instrumentation previously used on the space shuttle for inspecting the orbiter following launch.

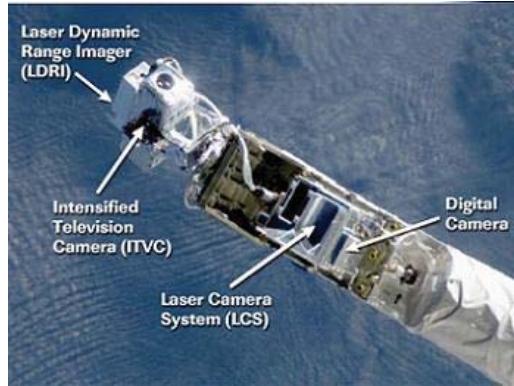


Figure 10. JSC Robotic Instrumentation.

The flight demonstration also starts preparing the launch facilities for the safety and security of launching a nuclear reactor under all potential abort scenarios. Some abort scenarios require the engine to be tested under those abort conditions for acceptability. A nuclear safety review and launch approval process is required and shown in Figure 11. The launch approval process could take up to 5 years to get final approval and needs to be accounted for in the overall development plan. Both strategies for ground testing and flight demonstration appear to show promise.

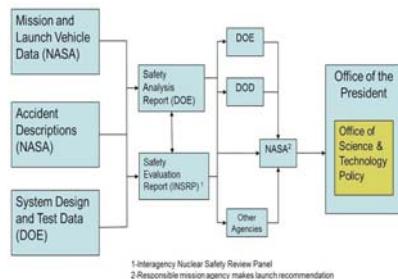


Figure 11. Nuclear Safety Review and Launch approval Process

III. Conclusion

The potential capability of NTP is game changing for space exploration. A first generation NCPS based on NTP could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Near-term NCPS systems would provide a foundation for the development of significantly more advanced, higher performance systems. For NTP to be utilized, an affordable development and qualification strategy must be devised.

Nuclear energy is the safest and cleanest energy source currently available. The NTP rocket can be designed to be safe and provided high performance to enable human space exploration. However, “NUCLEAR” is a word that is feared and vilified by some groups and the hostility towards development of any nuclear systems can meet great opposition by the public as well as from national leaders and people in authority. Communication and public policy of nuclear safety will be critical to the success of a viable and affordable NTP rocket.